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AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Propulsion Technical Memorandum 473

RESEARCH INTO IMPROVING THE DURABILITY OF THE HOT SECTION IN THE AIRCRAFT TURBINE ENGINE

by

N.S.SWANSSON

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RESEARCH INTO IMPROVING THE DURABILITY OF THE HOT SECTION IN THE AIRCRAFT TURBINE ENGINE

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SUMMARY

Propulsion Branch at ARL is reviewing the direction of its research activities into the integrity, durability and life extension of aircraft turbine engine components. Hot section repairs dominate the costs of engine overhaul, so resources are being redeployed from other programs on life of engine components towc this area of high potential benefit.

Engine hot section life is an area of great complexity and wide scope. Despite the technical difficulties and limits in resources, the Branch can make a useful contribution with carefully selected research. New areas or extensions proposed are structural analysis of high temperature components under cycles of thermal loading, and thermal analysis of components to determine temperature distribution which characterises the thermo-mechanical loading. While structural analysis can build upon existing related expertise, little experience exists in thermal analysis and its core discipline of heat transfer, so a program to build up this technology base is proposed and options are examined.

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1. INTRODUCTION

This report examines research activities at ARL relevant to life assessment and life extension of hot section components of aircraft turbine engines. Possible directions for research in this field by ARL Propulsion Branch are explored, having in mind the importance of producing results useful for dealing with problems in the Australian Defence Forces (ADF).

Combustor liners, nozzle guide vanes and turbine blades are the major components in the hot section of a turbine engine. Durability and life extension of these hot section components is of prime interest for economic reasons. Deterioration of hot components determines all major engine overhaul schedules, as hot section life is at most half that of other major engine systems or components. Engine overhaul costs are dominated by hot section repairs. With implicit flow-on costs to availability and operability, the engine hot section in total uses up the lion's share of engine life cycle costs.

Before embarking on their comprehensive Hot Section Technology (HOST) research program in the early 1980's, the National Aeronautics and Space Organisation (NASA) in USA carefully examined the justification for a program of such ambitious scope. Dennis & Cruse (1979) concluded that hot section repairs consume up to 70% of all engine overhaul costs, and estimated that a 30% increase in hot section life possible with advanced technology would result by the year 2000 in savings of $9000m ($A 1991) for the world's commercial jet airliner fleet.

In Australia, total engine investment in the RAAF fleet is about $1000m. RAAF hot section maintenance costs about $17m per year, of which the F404 engine in F/A-18 takes the largest share of about $7m (life cycle average). As well as contributing directly to maintenance costs, hot section deterioration also impairs aircraft operability and availability, where potentially very large indirect costs may be incurred.

Durability of the gas turbine engine has increased constantly since it was invented, and the new generation of advanced fighter engines being developed in USA have a design life twice that of the most modern engines in the RAAF. Nevertheless a trade-off is still needed between performance and durability in the hot section, since no engine has yet attained the effective performance ceiling of stoichiometric combustion. With fighter aircraft, performance is crucial so the trade-off is more toward high performance, hence durability is less than for engines in transport aircraft, helicopters &c. Whatever advances are made in materials, cooling, monitoring &c., the hot section is certain to have the shortest life and improved durability will continue to be a desirable objective.

2. ADF CONSIDERATIONS

2.1 Operator Considerations

Major benefits which the ADF can obtain from research into hot section durability and life extension, are reduced costs and improved maintainability and availability. The possible economic benefits are plain.

A focus on the hot section is justified not only because deterioration is relatively rapid and costs of repairs are high, but also because ameliorative repair schemes and modifications can be more readily implemented than in other mechanical parts of the engine. Generally speaking failure of the hot section is progressive and signs of deterioration can be observed, so that timely replacement or repair action is possible.

Non-rotating parts are very often suitable for repair or refurbishment, and it is common for overhaul authorities to implement local repair schemes. Qualifying a repair scheme and securing manufacturer approval is easier than for more critical components in the rotating assembly, partly because the consequences of failure are less severe and less likely to jeopardise airworthiness. Effective repair and refurbishment schemes are extremely cost effective and substantial savings can be realised.

Extensive weld repairs are common on combustion liners. Nozzle vanes are also repaired by welding or vacuum brazing. Repairs on rotating turbine blades are also possible but require more careful consideration. Recoating of turbine blades and rejuvenation of creep damage by Hot Isostatic Pressing are established practice; other repair schemes of limited scope are practised by specialist organisations (e.g. rebuilding tips of blades by weld repairs).

2.2 Australian Environment and Operations

All aircraft in the F/A-18 fighter fleet are fitted with an in-flight engine condition monitoring and data recording system, so distinctive features of Australian environment and operations are known for this aircraft. Peculiarly Australian factors may exist for other aircraft engines, but detailed historical data defining them generally does not exist, although fleet-wide factors such as climate and atmosphere are obviously known.

Australian usage of the F404 engine in F/A-18 is more severe than that of US and Canadian operators for several reasons (Faragher 1991):

- Average flight duration is shorter than for typical overseas operators, hence more cycles are accumulated per flying hour.
- More time is flown at the maximum power setting.
- Peak metal temperatures during a flight are, on average, higher.

The last is a climatic effect, as prevailing atmospheric temperatures tend to be higher in Australia than in USA and Canada, so the "average" operating temperature for the fleet will be higher. When engine intake temperatures are higher, the engine control system produces higher cycle and metal temperatures. Although a tropical atmosphere is paradoxically colder at high altitudes (which may afford some relief for time dependent deterioration), with cyclic failure modes the critical temperature is the peak experienced over the whole flight, and since this is higher there is a correspondingly higher peak strain amplitude.

Because the F/A-18 aircraft is fitted with an in-flight monitoring system, fairly complete details of engine usage are known for the whole fleet. Similar data are not available for aircraft such as the F-111C, where only two test aircraft have been instrumented for engine monitoring. A usage survey of limited duration was conducted by the RAAF and the manufacturer some years ago (Misenti 1983). It

showed that engine usage was probably marginally less severe than for the US Air Force, but that no variation of life limits was warranted.

2.3 Alternative Fuels

In Australia the ADF has placed some emphasis on the possible need to use alternative aviation fuels, generally described as high aromatics. These fuels of higher carbon/ hydrogen ratio produce more luminous flames, caused by the presence of carbon soot particles which are broadband radiators of heat and light. Higher radiative heat transfer and resultant increased combustor liner temperature have been measured in combustors burning such fuels. If metal temperatures are significantly increased in normal engine operation, combustion liner durability will be degraded.

Though flame radiation is certainly increased, detailed evidence is lacking on its importance for durability. Within the combustor, heat is transferred to metal surfaces partly by convection. Radiation contributes only a portion of the total heat flux, and flame emissivity can at most asymptote to unity. As combustion pressure increases, convective heat transfer increases relative to radiation. At high combustor pressures typical of modern engines, convective heat transfer is dominant. Hence the most potentially severe conditions are mitigated, because the more luminous flames produce smaller increases in wall temperature when temperatures are already very high than when conditions are less severe.

Tests conducted in USA at the Naval Air Propulsion Center, investigating the use of alternative fuels in aircraft turbine engines (Mosier & Karpovich 1988) led to a conclusion that no effect on engine durability could be discerned. However the generality of this conclusion is restricted because of the limited scope of testing. The main objective was to explore the effects of different fuels on engine performance, so judgements of durability were made after relatively brief tests.

In summary, the evidence available regarding the effect of alternative fuels on engine durability is not conclusive, and further investigation of effects on hot section life is needed to clarify the consequences should Australia need to utilise such fuels.

2.4 Life Extension, Repair and Refurbishment

Hot section repair and refurbishment schemes lead directly to life extension. There is also a prospect of developing and qualifying minor design modifications which will extend life, possibly associated with repair work.

To maximise such opportunities a multi-discipline approach is necessary, which must include expertise not possessed by ARL in manufacturing and repair technology as well as materials, engineering and possibly aircraft operations aspects. The original equipment manufacturer (OEM) generally has access to all this expertise in one organisation whose major focus is aircraft engines.

In the Australian context it would mean that aircraft propulsion engineers and materials scientists within ARL, plus overhaul and production technologists from RAAF or private industry overhaul bodies, would need to accept and keenly pursue a common objective. Such collaboration has been rare, but the potential rewards are high both in direct cost savings to the ADF and indirectly in the development of advanced repair technology in Australian industry.

3. RESEARCH REQUIREMENTS AND OPPORTUNITIES

3.1 Nature of Problem

The life of the aircraft jet engine has always been limited by deterioration of hot section components. Until recent years, most failures of hot components occurred under prolonged quasi-steady loading at high temperatures, and were caused by creep deformation which led ultimately to rupture. More recently, particularly for fighter aircraft which undergo rapid throttle changes during combat manoeuvres, fatigue failure modes which are cycle dependent have become dominant in the hot section.

When the throttle position is varied, hot section components are subject to changes in heating and cooling, and with changes in speed, turbine blades are subject to changes in rotational loading. The major loading is due to thermal stress, generated by temperature gradients within components, and possibly also by external constraints which restrict thermal expansion. Cyclic loads are determined by general and local component temperature histories. Appreciating component loading therefore requires knowledge of component temperature levels and internal temperature distributions, and temperature values in turn depend on heat transfer and cooling processes operating upon and within the component.

Components subject to large temperature and strain cycles will deform permanently, warping or developing buckles, and ultimately crack. This is termed thermo-mechanical fatigue (TMF) and is characterised by concurrent cycling of temperature and strain. The typical mode of failure is similar to the more familiar high strain Low Cycle Fatigue (LCF) in so far as the component is subject to strain cycling. But in TMF not only do material properties vary with temperature changes throughout a thermo-mechanical cycle, but new types of microstructural changes may occur which do not take place at all in isothermal strain cycling.

3.2 Scope Of Research Activities

Research work performed under the NASA sponsored Hot Section Technology (HOST) project, which in 1987 completed a 7 year program (Sokolowski 1989), gives a guide to the scope of disciplines seen as necessary to advance hot section durability in aircraft engines. Programs were set up in the areas of instrumentation, combustion, turbine heat transfer, structural analysis, fatigue and fracture, and surface protection.

It will be seen below (§5) that ARL currently is undertaking research in most of these areas, though the research thrust is not necessarily directed to hot section problems. It is suggested that research activities in combustion and surface protection are relevant, well focussed and of reasonable depth. Research is taking place in structural analysis, and in fatigue and fracture, but the focus is not on engine hot section problems. Greater attention to hot section problems is needed to produce results which can be usefully applied.

A recent conference discussing life assessment for combustion turbine hot section components (Viswanathan & Allen 1990) spelled out the state of the art among gas turbine operators (in distinction to OEM's). Through specialist industry and university consultants, US operators have access to advanced technology at a level approaching the OEM, including much of the technology base developed through the HOST program. To provide advice to the ADF at a level comparable with other users, ARL needs a working knowledge of a number of advanced life assessment techniques.

3.3 Engine Overhaul and Manufacturing Technology

The above-mentioned conference also covered repair technology for combustion turbine hot section components (Viswanathan & Allen 1990) and showed the scope of this industry, where specialist firms provide repair techniques which offer operators substantial savings. Many of these techniques are available in Australia and because of the high value added, setting up of others is justified even for a modest market.

Existing industry in Australia includes turbine blade manufacture by casting and forging, fabrication and advanced welding technologies, advanced machining such as laser hole drilling, and surface coating technologies. Access to other advanced refurbishment technologies could be secured by license if needed for repair work .

Local implementation of new repair and refurbishment techniques offers an opportunity to the Australian engine overhaul industry. ARL does not have advanced skills in manufacturing technology, so industry support is needed to realise the opportunity.

4. PREVIOUS RESEARCH IN RELATED TOPICS

4.1 Low Cycle Fatigue Life of Engine Components

ARL has pursued programs of basic research into the performance of advanced aircraft engine materials, such as those used for rotor discs. A program of experimental and analytical research into Low Cycle Fatigue (LCF) of engine rotor components was maintained for over a decade, to build up a technology base in this area. LCF phenomena are now understood reasonably well, in contrast to the limited knowledge when research began.

Compared with hot section components where repair and refurbishment are common, application of LCF research results to engine rotor design is very difficult to accomplish. Components are discarded when their safe life expires. Should research lead to suggestions for a change in design, offering an improvement to engine rotor life, it would be exceedingly difficult to have any resulting modification accepted and approved by the engine manufacturer.

For these and other reasons, LCF research no longer has a high priority in Propulsion Branch and it has been discontinued for want of resources. Research into the life of hot section components can utilise some of the knowledge and methodology of LCF life which has been built up. Hot section life also introduces various difficult and challenging new technical problems, as outlined in §3.2.

4.2 Other Fatigue Life Research

After some four decades of research in the field, ARL has a world-wide reputation in the structural fatigue life of aircraft, and fatigue life assessment remains the primary task of Aircraft Structures Division. ARL maintains a very high level capability in structural fatigue; some aspects are relevant to engine component life so strong support is available, within the particular area of common interest.

Propulsion Branch became involved in fatigue life assessment in the early 1970's, when questions arose concerning the safe life of transmissions of Wessex and Sea King helicopters. Analysis of transmission fatigue life using operational load data led ultimately to the development of an in-flight Fatigue Life Usage Indicator.

The technology base and expertise developed in low cycle fatigue of engines, in gearbox fatigue life, and in aircraft structural fatigue has aspects in common, and is partly transferrable to the problems of thermo-mechanical fatigue in hot section components. TMF introduces many new problems, but for generic fatigue aspects a sound knowledge and resource back-up is available.

4.3 Development of Materials for High Temperature Components

At ARL many years ago considerable experience was acquired, both by materials specialists and by gas turbine engineers, in the development of chromium base alloys for very high temperature operation of gas turbine rotor blades. An experimental turbine with cooled NGV's was constructed, and rigs for thermal cycling of blade cascades were operated. Tests conducted gave first hand experience in problems of turbine blade manufacture and operation, hot section instrumentation, life assessment &c. Some of this knowledge would be relevant to current problems of hot section durability. The work ceased some years ago and though some residual expertise remains, much has been dissipated.

5. CURRENT RESEARCH IN RELEVANT AREAS

5.1 Propulsion Branch Facilities

While access to major facilities does not dictate the direction of research, their availability creates opportunities which should not be ignored. Two Propulsion Branch facilities warrant mention.

Blowdown Facility: A high pressure intermittent blowdown facility is able to supply up to 45 kg/sec of air at pressures up to 7 MPa, with a minimum run time of 11 sec. It has a regenerative heat exchanger able to heat the air to 400°C. Although it has not been possible to operate this facility to its full capacity, even at reduced rating it would offer a world class capability for turbine heat transfer research. Because it has a heat exchanger, isentropic compression is not required for heating the air, and it can provide the same transient test conditions as the more complicated piston tunnel (Jones 1988).

Combustion Test Facility: A modern combustion test facility is about to be commissioned, capable of supplying 9 kg/sec of air at pressures to 3 MPa, with combustor preheat so that unvitiated air is available at temperatures up to 650°C. The principal purpose of this facility is to supply air at a wide range of conditions for combustion testing. In this normal mode, research employing a specially instrumented combustor for heat transfer measurements could be conducted. Durability tests on combustor liners and blade cascades, in a realistic hot gas environment, are an obvious possibility.

If compressor surge can be avoided, it may be possible to adapt this facility for transient heat transfer investigations, using the preheated air with a fast switching diverter arrangement between spill and test sections.

5.2 Combustion

Propulsion Branch has a strong background and experience in experimental combustion research, which has produced excellent results when problems could be solved by straightforward scientific and engineering development. Hot section life can be extended by improving the temperature distribution produced by the combustor, thereby reducing peak metal temperatures in critical locations on the liner. It is also possible to improve the circumferential and radial pattern factors at the combustor outlet, thereby extending nozzle guide vane and turbine blade life.

These approaches have been applied with some success to T56 engines in the RAAF, and similar methods are being utilised in trying to alleviate thermal fatigue cracking in the TF30 combustor liner.

Practical investigations have been very effective but analytical methods for quantitative appreciation of benefits, trends &c. have not been developed to a comparable level. Furthermore without a capability to model combustion flow and heat transfer, enabling the prediction of liner wall temperatures, even the simplest variation in configuration can be evaluated only by experiment which is relatively expensive.

5.3 Engine Thermodynamics

For the F/A-18 engine, usage data takes the form of time records of parameters such as as Power Lever Angle, LP and HP spool speeds, exhaust gas temperature &c. An adequate engine model is required to generate accurate values of local gas temperatures and other parameters needed for hot section life analysis. Mainly to facilitate diagnosis of engine faults, Propulsion Branch has developed a strong capability in performance analysis of both steady state and transient engine behaviour. This capability is more than adequate to support assessment of engine hot section durability.

5.4 Life Usage: Engine Components and Helicopters

A comprehensive program assessing LCF life usage of the F404 engine in Australian operational conditions has just been completed. There is little need for further usage assessment of this engine unless aircraft roles are changed. At this time an excellent understanding exists of the state of the art in LCF usage assessment, which can provide a basis for appreciating the more complex issues of hot section life assessment.

ARL has also been asked by the RAAF to develop the science of fatigue life monitoring in helicopters. A flight measurement program for the S-70A-9 Black Hawk helicopter may be undertaken in the foreseeable future. A working knowledge of helicopter lifing methodology has been built up, anticipating the need to analyse flight fatigue usage data. ARL will be able to make an independent assessment of life when data is available. Helicopter lifing methodology has similarities to engine LCF life usage and to gearbox fatigue life. The work is further building a fatigue technology base of relevance to hot section life.

5.5 Structural Analysis

Structural analysis methods for component stress/ strain analysis have been used in engine LCF research for some years. The PAFEC finite element package at ARL is most widely used but other packages have been used when appropriate. Some specialist competence has been acquired in modelling of elasto-plastic strain in components representative of engine rotor discs (Swansson 1986).

The HOST program led to considerable advances in structural analysis capabilities in USA. Developments such as component specific modelling, probabilistic structural analysis and application of boundary elements enabled much greater detail in the analysis of the large structural problems, including more faithful representation of boundary conditions. Access to many of these capabilities is available to manufacturers, universities and consultants within USA but is difficult for organisations outside.

Many problems can be treated without these super programs; ordinarily available finite element packages are often adequate. However current experience is that programs available to ARL have more fundamental deficiencies in that they cannot model repeated sequences of plasticity and creep processes which occur with thermal cycling at high temperatures.

When a component is loaded either mechanically or thermally, conventional material descriptions partition its inelastic strain response into time independent and time dependent terms, each independent of the other and defined by a particular constitutive equation. Plastic deformation, normally occurring only in local regions where stress/ strain levels are most severe, is assumed to be instantaneous and independent of time. Creep or stress relaxation is a function of time, and occurs at higher temperatures when a stress level less than that required for plastic deformation is sustained for a long period.

Usually plasticity and creep occur in different regimes and do not interact. However in the turbine engine hot section, conditions include thermal loading which is applied relatively quickly, plus hold periods of varying duration at high temperature levels. Plasticity and creep generally interact in this environment. However the simplest analysis treats them as independent and solves for small sequential increments, alternating plastic strain and creep.

This simplified approach is not possible with PAFEC level 7.0 which is unable to model creep which follows plastic strain, or vice versa. Some finite element solvers (e.g. MARC) are known to possess this ability. A trial problem is being run to determine whether the more readily available packages (ANSYS, ABAQUS) are suitable. MARC is used in USA and UK because its particular capabilities are the most suitable for this type of problem, but it is not installed on any computer in Australia.

5.6 Constitutive Modelling

In the engine hot section environment, plastic and creep behaviours interact and the conventional model of independent processes is inadequate. To overcome this, alternative constitutive models for materials have been developed over the last decade, employing total inelastic strain (plastic + creep) as a principal variable. These models utilise state variables, which notionally represent the microstructure which evolves during the loading history of the material.

To support research in aircraft structures, ARL has worked with Prof. D.C.Stouffer to implement the Bodner-Stouffer state variable constitutive model (Bridgford 1989) into the PAFEC finite element package at ARL. ARL interest so far has focussed on the structural alloy Aluminium 7050, but Stouffer had previously determined model parameters for the nickel base superalloy René 80, used in a number of hot section components in the F404 engine. Similar parameter values were not available for Hastelloy X, used in combustors in both TF30 and F404 engines, so Propulsion Branch is using available generic material data to obtain the best possible approximations for these values.

5.7 FATIGUE DAMAGE AND LIFE: LCF AND TMF

A great deal of LCF life data pertinent to damage calculation and life estimation was acquired during the engine LCF life program (§4.1). A reasonable appreciation of practical LCF life prediction exists, though test experience is limited. This expertise is partly relevant to hot section TMF life.

Ongoing research in aircraft materials aims to characterise LCF properties of turbine disc materials. Operating temperatures are lower and disc materials are of different composition from the superalloy materials employed in the hot section. Disc behaviour can be characterised adequately by isothermal tests, whereas hot section materials are subject to full TMF cycling and testing under similar TMF conditions is needed to properly define their performance. ARL has no TMF testing capability, and existing isothermal facilities are not being used for hot section materials.

5.8 SURFACE PROTECTION: COATINGS FOR HOT SECTION

ARL has recently assumed responsibility for research on coatings for hot section components and has built up an active materials research program. Initially it is likely that an inexpensive low velocity rig will be used for preliminary coating research, but use of Propulsion Branch facilities may be needed for more realistic proving tests. A requirement for testing under simulated engine conditions of combustion products and gas velocity, which is much more expensive in equipment and running costs, could arise if full qualification of a coating were sought.

Propulsion engineers tend to view corrosion/ oxidation resistant coatings as protecting a structural substrate so that it maintains its intrinsic strength, which is achieved as long as the coating integrity is preserved. The engineering function of a coating is more significant with advanced Thermal Barrier Coatings (TBC's) which insulate the substrate so reducing its temperature. TBC's are not used in present generation engines in Australia, though an experimental application is being considered.

6. AREAS FOR FURTHER RESEARCH IN PROPULSION

This section examines areas of research under control of Propulsion Branch where, in order to develop viable capability in hot section life extension, current research should be maintained, modified or strengthened, or new research should be initiated. Considerations in recommending a particular area are:

- Past experience in the area, existing knowledge and level of expertise.
- Facilities available or facilities required.
- Level of resource input (staff, funds) required for viable activity.
- Output which is possible with resources likely to be available.
- Balance of overall capability: need for specialist skills of particular sub-area in order to address general problem.

6.1 Structural Analysis and Constitutive Modelling

The difficulty of securing access to advanced component-specific structural analysis codes, used in USA for life prediction, has been mentioned. It is the author's view that existing finite element codes, with which ARL is familiar, can model problems of limited scope with acceptable fidelity, and lack of advanced computational facilities is not an insuperable handicap at present.

However PAFEC'S present inability to model sequential plastic and creep deformations renders it unsuitable for hot section component modelling. Possible alternatives are:

- MARC is known to be suitable, but has not been installed at any Australian location. It could be purchased (expensive) or run offshore (unwieldy).
- If tests prove that ANSYS or ABAQUS is suitable, computer time could be bought at an Australian installation or the package could be purchased (also fairly expensive).
- State variable constitutive models allow interaction of plasticity and creep by combining them in a total inelastic strain. ARL has already incorporated the Bodner-Stouffer model into the PAFEC FE package (Paul et al 1990), but at the present time only isothermal loading has been considered. PAFEC would need to be further extended to include thermal loads and to enable the determination of element properties as a function of a varying Gauss point temperature. This option costs little but requires input of specialist effort.

Availability of a structural analysis tool is essential and it is recommended that research continue to obtain one which is suitable. Considerable work has already been done in this area, so continuing research will build up expertise already developed.

6.2 Thermal Analysis: Heat Transfer

It has been emphasised (§3.1) that loading, i.e. local strain, of hot section components is determined essentially by the temperature distribution, and naturally the local material strength depends on its temperature. Constraints on hot components (often generated internally by differential expansion) cause thermal strains. Applied mechanical loads (other than constraints) are of secondary importance and often are negligible. In modern engines, even for the rotating blades, failure tends to be caused by thermal rather than rotational loading. Sokolowski & Ensign (1986) indicated that characterising of thermo-mechanical loads was a major objective of the NASA HOST program.

Direct experimental measurement of component temperature might appear to be the best way of meeting the need for temperature definition. Reasonable precision is required, especially for thermal gradients, where high resolution both in temperature and space is needed to achieve the desired accuracy. Surface temperature

measurement in the hot section is extremely difficult; all techniques have both advantages and limitations. ARL has considerable experience with thermal paint techniques and in the application of miniaturised thermocouples, and limited experience with non-contact infra-red thermometry. Other advanced surface temperature techniques such as Laser Induced Fluorescence (LIF), which have particular advantages, are now available. It is recommended that ARL maintain expertise in advanced temperature measurement, and that new techniques be kept under review.

Local temperatures must be found by thermal analysis in order to characterise thermo-mechanical loading on components. Direct measurement is insufficient in virtually all practical problems, and even if measurements are taken complementary analysis is needed. Temperatures of combustor liners and blades depend on heat transfer processes in internal passages and on external aerofoils, endwalls and other surfaces. Heat flux on various surfaces of components is caused by radiation, convection, impingement and film cooling processes, and various devices are employed to enhance heat transfer (ribs, pin fins) or impede it (thermal barrier coatings).

Other than in limited areas (aerodynamic heating in hypersonics, fabrication and testing of cooled NGV's) ARL has not in the past conducted any systematic research into heat transfer, or turbine heat transfer in particular. ARL's dearth of expertise in heat transfer was apparent recently, when Prof.T.V.Jones of the University of Oxford provided consulting advice on practical RAAF turbine problems. ARL aims to increase its knowledge base by modest support of a heat transfer research investigation at the Osney Turbomachinery Laboratory of Oxford University, and by fostering relationships with heat transfer researchers at Australian universities.

Improvements in blade cooling more than anything else are responsible for the substantial increase in gas turbine efficiency, consequent on increasing turbine entry temperatures, which has been attained over the past couple of decades. Heat transfer is a key expertise required in modern turbine engine design and substantial research is conducted and published, and it is recommended that research in turbine heat transfer be initiated within Propulsion Branch.

Turbine heat transfer embraces a range of relatively specialised topics, such as:

- Film cooling: principles, analysis and prediction methods.
- Radiative heat transfer: luminous flames, high combustion intensity.
- Gap flow and heat transfer: blade tips, shrouds, labyrinth seals, squealer tips &c.
- Convective heat transfer to blade aerofoils.
- Rotating flow passages: Coriolis effects, high "g" buoyancy.
- Jet impingement cooling.
- Enhancement of convective heat transfer: ribs, pin fins &c.
- Effectiveness of thermal barrier coatings.

It is not appropriate to explore all the options for turbine heat transfer research in this report. Suffice it to say that the topics listed offer both scientific challenge and technical utility, and useful results are practically realisable at reasonable resource levels. The Branch has facilities, both the transient capability in the blowdown tunnel and the CTF, which are suitable for various forms of advanced testing. Combustion test facilities and rigs already exist for research on flame radiation and combustion liner heat transfer, forming a springboard for the developments needed in

instrumentation. An investigation into the use of Branch facilities for heat transfer research, culminating in a design proposal, is therefore recommended.

6.3 COMBUSTION

The imbalance between the Branch's strong background in combustion experiment, and its relative lack of activity in combustion analysis, is now being redressed. With an increasing interest in modelling combustion processes and combustor heat transfer, a better ability to predict effects of modifications and evaluate trade-offs will become available. This expanded emphasis should receive full endorsement.

Predicting the temperature of combustor liners requires knowledge both of heat transfer and combustion. Practical investigation of radiant and total heat flux on combustor liners, and development of associated predictive models, is recommended. The experimental aspect of this could be achieved with relatively minor changes to test programs already contemplated.

If a practical problem on hot section life arises which requires tests under a realistic environment, existing combustion test rigs and facilities would provide the source of hot combustion products. Such testing associated with combustion testing, is envisaged more for problem solving than for more basic research, but it exemplifies the desirability of maximising the interaction between durability and combustion testing.

6.4 ENGINE LIFE USAGE

Compared with cycle counting for LCF usage, parameters for assessing hot section usage are more difficult for the engine operator to quantify, and algorithms for estimating life usage necessarily make simplifying assumptions. For the F404 engine, the algorithm approximately predicts engine cycle temperature from engine and environmental parameters, and then estimates blade metal temperatures from an empirical correlation. Damage for each major cycle (lesser cycles are disregarded) is assumed to depend on the estimated maximum metal temperature, which is used to calculate an empirical weighting factor.

A simplified life prediction methodology is used in the U.S.Navy LIFER program, which has been used for verifying hot section usage estimates (Swansson & Cyrus 1987). Normally only the effect of time at temperature is considered in predicting failure by stress rupture (Bentz & Coté 1991). To calculate life of combustor liners under thermal cycling, Foltz & Kenworthy (1986) assume that temperature gradients and thermal strains are proportional to the difference between liner metal and cooling air temperatures. Similarly the author has modified LIFER to estimate turbine blade TMF life, assuming that thermal strain is proportional to the difference between gas entry and cooling air temperatures. Accumulated cyclic damage in thermal fatigue is then calculated in a similar way to LCF, using isothermal material properties.

Better life usage measurement can be achieved, by using advanced measurement and estimation algorithms to compute life consumption throughout each flight. At present US and UK operators of Pegasus engines fitted to AV-8B Harrier aircraft are deciding whether there is justification for a Rolls-Royce recommendation to use such a system, which would require additional on-board computer power.

Until recently life usage measurement has used only simple processes, obviously capable of refinement. Propulsion Branch has developed a sound appreciation of LCF life usage, but a similar appreciation for TMF is not so well developed, because measurement of hot section life usage is more complex. Expertise in usage measurement comes as a spin-off from life prediction and work in this area should proceed in parallel with other TMF life investigations.

6.5 High Temperature Fatigue and TMF Life

In aircraft materials research, ARL is active in the field of high temperature fatigue of turbine disc materials, but is not presently working with superalloys for combustor liners or blades at the higher hot section temperatures. Existing equipment can perform isothermal fatigue testing up to about 1000°C, roughly the maximum metal temperature of F404 turbine blades but now exceeded by modern blade designs. ARL does not have facilities capable of simultaneous temperature and strain cycling needed for experimental research in thermo-mechanical fatigue.

Life prediction methodology requires fatigue damage algorithms which are ordinarily generated from multitudinous material fatigue tests. A large volume of data has been published on high temperature fatigue, some giving damage and failure criteria, and the review by Halford (1989) presents a typical glimpse of the wider picture.

Without data from samples of specific materials of interest, life prediction must use whatever generic material data is available. Fortunately both monotonic and cyclic stress-strain data (for constitutive model development) and fatigue life data are available for Hastelloy X, used for combustor liners in both TF30 and F404 engines. Data for some blade materials (René 80) is reasonably available; for others (Udimet, Waspalloy, directionally solidified alloys) it may be scarcer.

Acquisition of data for specific materials would require facilities which Propulsion Branch does not have, and extra resources would be needed whether the work is done within ARL or externally. Specific material data, including that from experiments designed to determine values of parameters in constitutive models, is desirable. However for purposes of analysis and life prediction sufficient generic data exists to tackle problems in sight at present.

The conduct of thermal fatigue tests with actual hardware (i.e. blade cascades) in a combustion rig simulating the engine environment generates problem specific fatigue data. Testing is expensive, and in such tests many variables are unknown so results are relevant only to the specific problem being simulated. Full environmental simulation is the only positive means of component life validation, but its cost is justified only when there is a priority need for this data.

7. CONCLUSIONS AND RECOMMENDATIONS

1. Engine hot section life prediction and life extension is an area of great complexity and very wide scope. Neither Propulsion Branch nor even all of ARL can muster all the resources to cover it in detail, or to match the capabilities of engine manufacturers in the area.
2. Nevertheless by selective development of technology base expertise, combined with use of available published data, a sufficient competence can be developed for predicting trends or the effect of modifications, for examining effects of Australian usage, and for solving specific problems.
3. Although OEM's and operators in USA now have access to advanced structural analysis codes such as component specific modelling, it is possible to model smaller problems adequately with available finite element codes.
4. To compute component strains under the thermo-mechanical load cycles applied in the hot section, a FE package must at least have the capability to model repeated sequences of plastic and creep response. Preferably it should employ the more recently developed state variable constitutive models for materials, which allow creep-fatigue interaction. A FE package having this capability must be acquired or ARL must further upgrade the existing capability of the in-house PAFEC package for hot section problems.
5. Prediction of local component temperatures is required to characterise the pattern of thermo-mechanical loading applied to the hot section. To perform the necessary thermal analyses, expertise needs to be developed in the key discipline of heat transfer.
6. Though advances in the application of heat transfer are central to the great improvements in modern turbine design, ARL lacks experience in the field. However it has major facilities which are suitable for advanced heat transfer research. A design study of the available facilities to plan a heat transfer research rig should be initiated.
7. Measurement of component surface temperatures complements thermal analysis. ARL should monitor advanced techniques such as Laser Induced Fluorescence (LIF) and implement them when appropriate.
8. The increased emphasis on modelling in combustion research should be maintained, including objectives of predicting gas temperatures and flow parameters which determine heat transfer.
9. Maximum opportunity should be taken in combustion testing to gain knowledge of durability aspects, and to acquire data relevant to combustor heat transfer. Measurements of radiant heat flux and total heat flux at combustor liners should be obtained. Efforts should be made to develop specialised instrumentation for these difficult measurements, using opportunities created by tests conducted within other combustion research programs.
10. For materials of current interest available generic data is sufficient for initial analysis. Generic data varies in quality and comprehensiveness. Plainly, specific material data is preferable and may be needed, particularly if the ADF seeks better solutions for important specific problems.

8. REFERENCES

Bentz,J.C. & Coté,S.M. "Verifying Conceptual Design Gas Turbine Blade Life Predictions by Comparison with Fleet Data" *ASME Paper 91-GT-326* 1991

Bridgford,N. "A Summary of the Bodner-Stouffer Constitutive Model" *DSTO ARL Tech Memo ARL-STRUC-TM-513*, 1989

Dennis,A.J. & Cruse,T.A. "Cost Benefits from Improved Hot Section Life Prediction Technology" *AIAA Paper 79-1154, AIAA/ SAE/ ASME 15th Joint Propulsion Conf*, 1979

Faragher,J.S. "Component Life Estimates for the RAAF F404 Engine with a Comparison of Life Calculations" *DSTO ARL Report ARL-PROP-R-186*, 1991

Foltz,H.L. & Kenworthy,M.J. "Procedure for Evaluating Fuel Composition Effects on Combustor Life" *AIAA J Propulsion & Power* 2 366-370 1986

Halford,G.R. "Thermal Fatigue Durability for Advanced Propulsion Materials" *3rd Australian Aeronautical Conference, Melbourne*, 488-492 1989

Jones,T.V. "Gas Turbine Studies at Oxford 1969-1987" *ASME Paper 88-GT-112*, 1988

Misenti,J. "F-111C/ TF30-P-3 Mission Analysis" *Paper on Item M-25 TF30 Engine Usage Validation, CIP User Meeting*, 9 August 1983

Mosier,S.A. & Karpovich,P.A. "Fuel Property Effects on the US Navy's TF30 Engine" *AGARD-CP-422 PEP Symposium on Combustion & Fuels in Gas Turbine Engines*, 1988

Paul,J.J., Bridgford,N. & Stouffer,D.C. "Progress Report on the Implementation of a Constitutive Model into the PAFEC Finite Element Package" *DSTO ARL Tech Memo ARL-STRUC-TM-529*, 1990

Sokolowski,D.E. & Ensign,C.R. "Toward Improved Durability in Advanced Combustors and Turbines: Progress in the Prediction of Thermo-Mechanical Loads" *ASME Paper 86-GT-172*, 1986

Sokolowski,D.E. (ed) "Toward Improved Durability in Advanced Aircraft Engine Hot Sections" *NASA Tech Memo 4087*, 1989

Swansson,N.S. "An Application of Finite Element Methods with Cyclic Elasto-Plastic Strain Analysis to Low Cycle Fatigue Problems of Engine Components" *DSTO ARL Report ARL-PROP-R-174*, 1986

Swansson,N.S. & Cyrus,J.D. "Application of Engine Component Life Methodology to Life Assessment" *8th Intern Symp on Air Breathing Engines, Cincinatti, Ohio, USA*, 486-493 1987

Viswanathan,R. & Allen,J.M. (eds) "Life Assessment and Repair Technology for Combustion Turbine Hot Section Components" *Proceedings EPRI/ ASM Conference, Phoenix, Arizona, USA* April 1990

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16. ABSTRACT

Propulsion Branch at ARL is reviewing the direction of its research activities into the integrity, durability and life extension of aircraft turbine engine components. Hot section repairs dominate the costs of engine overhaul, so resources are being redeployed from other programs on life of engine components toward this area of high potential benefit.

Engine hot section life is an area of great complexity and wide scope. Despite the technical difficulties and limits in resources, the Branch can make a useful contribution with carefully selected research. New areas or extensions proposed are structural analysis of high temperature components under cycles of thermal loading, and thermal analysis of components to determine temperature distribution which characterises the thermo-mechanical loading. While structural analysis can build upon existing related expertise, little experience exists in thermal analysis and its core discipline of heat transfer, so a program to build up this technology base is proposed and options are examined.

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